TRANSIENT NUMERICAL STUDY ON ENHANCEMENT OF PHASE CHANGE MATERIAL THERMAL STORAGE WITH ANGLED PARALLEL FINS

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ABSTRACT

We present numerical investigations on a thermal energy storage (TES) system using organic phase change materials (PCMs) of RT42 for energy recovery from a heat source. To enhance the heat transfer rate, five types of parallel fins with different oblique angles of 0°, ±15° and ±30° are proposed. A transient numerical model is developed to simulate the PCM melting process with considering natural convection. The simulation settings are well validated by the experimental tests. The contours of melting fraction with natural convection driven flow are clearly performed and compared. The level of enhancement is determined by the average melting fraction of PCM domain varying with time. The angled fins show better performance than the 'No Fin' one. Enhancement ratio is also introduced to qualify the oblique angle effect. Results indicate that PCMs with −15° fins melt faster than the other types and has a maximum 10% improvement on the basic case of 'No Fin'. As the angle of fins increases to −30° or +30°, the enhancement decreases.

INTRODUCTION

Over the last decades, thermal energy storage (TES) systems, especially latent heat thermal energy storage (LHTES), have gained extensive attention from the perspectives of energy-efficiency improvement [1]. LHTES employs phase change materials (PCMs) as storage mediums to store and release heat by reversible liquid/solid phase transformation. The PCMs thermal energy storage can improve energy efficiency while minimizing the mismatch between the energy supply and demand. Besides, compared with sensible energy storage, it exhibits superior efficiency and dependability because of its high storage capacity and nearly constant thermal energy. Therefore, LHTES with PCMs have been intensively applied in different engineering fields such as building [2], electronic products [3], waste heat recovery [4], etc. However, PCMs, using as thermal storage mediums, have a remarkable drawback: a low thermal conductivity for heat transfer, which makes longer of the melting or solidification time when store or release the thermal energy, and thus seriously hinders their practical applications for energy storage [5]. It is an important subject to enhance the heat transfer inside PCMs. Researchers have developed various techniques, such as the use of fins[1], insertion of metal matrix in the PCMs [6], PCMs dispersed with high conductivity particles [7] and so on. Among these tools, fins are the most common ones used because they are easier to fabricate and cost lower. Various fin configurations are applied to PCMs. Sciacovelli et al. [8] proposed tree shaped fins to enhance the performance of a shell-and-tube LHTES unit. The geometry of Y-shaped fins with one and two bifurcations are optimized through the combined use of CFD modeling and response

NOMENCLATURE

c_p	[J/kg·K]	Heat capacity
d	[m]	Distance between neighbor fins
$\vec{g}$	[m/s^2]	Gravitational acceleration
H	[kJ/kg]	Enthalpy
ΔH	[kJ/kg]	Latent enthalpy
h	[kJ/kg]	Sensible enthalpy
k	[W/m·K]	Thermal conductivity
L_h	[kJ/kg]	Latent heat of fusion
l	[m]	Length of fin
p	[pa]	Pressure
q	[W/m^2]	Heat flux
T	[°C]	Temperature
T_l	[°C]	Melting Temperature
T_s	[°C]	Solidification Temperature
t_f	[m]	Thickness of fin
$\vec{u}$	[m/s]	Velocity vector

Special characters

β	[K^{-1}]	Thermal expansion coefficient
γ	[1]	Liquid fraction
θ	[°]	Oblique angle of fins
μ	[kg/m·s]	Dynamic viscosity
ρ	[kg/m^3]	Density of PCM
ρ_l	[kg/m^3]	Density of PCM in liquid state
ρ_s	[kg/m^3]	Density of PCM in solid state

Subscripts

l	Liquid state
ref	Reference
s	Solid state

surface method. Their results show that an increase of 24% of the system efficiency can be achieved. Sheikholeslami et al. [9] also designed an innovative fin configuration based on snowflake crystal structure to enhance the performance of LHTES during the discharging process. They found that enhancement of discharging process in LHTES by applying snowflake shaped fin structure is high significantly, and it does not reduce maximum energy storage capacity considerably. Other researchers also conduct researches on fin's geometry, number, length or thickness to see their effects on PCM melting. One of most important reasons why fins can enhance the PCM melting is because they increase heat conduction area. Meanwhile, natural convection driven by buoyancy force has reported [10] as another important role when PCMs melt from solid to liquid. In this work, we propose five parallel fins designed in different oblique angles and apply them in a PCM-based heat recovery system. To investigate the heat transfer enhancement during PCM melting, a two-dimensional time-independent numerical model is developed in consideration of natural convection. The model is validated firstly and then used to simulate the thermal behavior during 16000s heat recovery process. The results of five type fins will also be preformed and analyzed.

NUMERICAL APPROACH

Physical Model

The schematic diagram of experimental setups for the PCM-based heat recovery tests is shown in Fig. 1. The nature of the geometry used and the experimental methodology of studies enable the simplification of the system to a two-dimensional model. The heater plate made by copper works as a heat source. It is vertically placed with a dimension 20×100 mm, and the heater input is determined by a heat flux, q, at one side. Next to the heater, a cavity full with PCMs measures 120×100 mm, which is enclosed within a stainless steel rectangular container with a thickness 1.5 mm on the right and bottom sides, and 3 mm on the top. The container is well wrapped by insulating materials to prevent the heat transfer with surrounding air.

To increase the melting rate of PCMs, models with parallel fins in a oblique angle θ from 0°, ±15° to ±30° are proposed and drawn in Fig. (2) as well as no fin one. The key emphasis in this work is to study the effect of fin's oblique angle so that other parameters such as length of fins l, thickness of fins t_f and the distance between neighboring fins d are all set with constants as: $l = 45$ mm, $t_f = 2$ mm, $d = 32$ mm.

The commercial paraffin, RT42, from Rubitherm GmbH company with a melting temperature range from 38 °C to 42 °C is selected as the PCM. Table 1 shows its thermophysical properties together with the materials copper and stainless steel used.

Governing Equations

In order to simulate the melting process of the PCMs, the enthalpy-porosity approach proposed by Voller et al. [11] is employed. In this approach, the melt interface is not tracked explicitly. Instead, the liquid fraction is computed at each iteration, based on an enthalpy balance. The liquid-solid mushy zone is

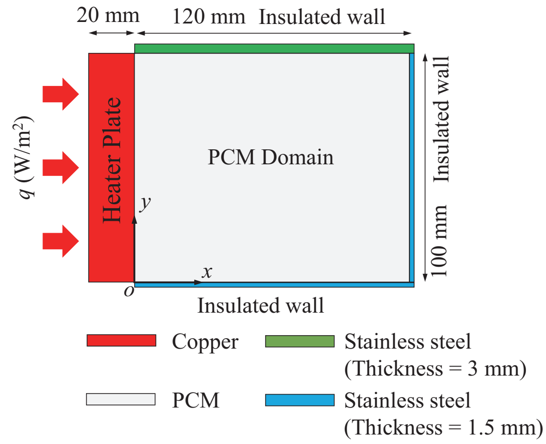

Figure 1. Model geometry and boundary conditions setup.

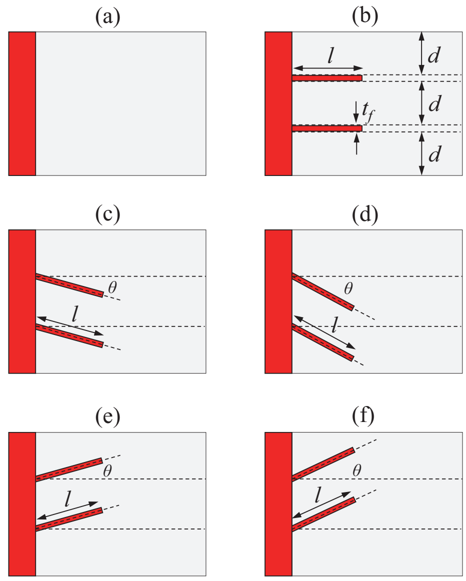

Figure 2. Configurations for (a) no fin, parallel fins in oblique angle θ at (b) 0°, (c) −15°, (d) −30°, (e) +15° and (f) +30° (Fin length $l = 45$ mm, thickness $t_f = 2$ mm and distance $d = 32$ mm).

treated as a porous zone with porosity equal to the liquid fraction, and appropriate momentum sink terms are added to the momentum equations. The effect of natural convection during melting is considered by invoking the Boussinesq approximation, which is valid for the density variation of buoyancy force:

$$\rho = \rho_l / (\beta(T - T_l) + 1) \tag{1}$$

where ρ_l is the density of PCM at the liquid state, and β is the thermal expansion coefficient.

The governing equations used here for modeling the PCM-based heat recovering system are,

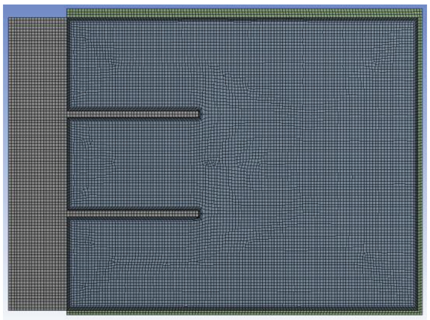

Figure 3. Mesh generation with 17215 elements for the parallel fins when oblique angle $\theta = 0°$.

(a) continuity equation,

$$\frac{\partial}{\partial t}\rho + \nabla \cdot (\rho \vec{\boldsymbol{u}}) = 0, \tag{2}$$

(b) momentum equation,

$$\frac{\partial}{\partial t}(\rho \vec{\boldsymbol{u}}) + \nabla \cdot (\rho \vec{\boldsymbol{u}}\vec{\boldsymbol{u}}) = \mu \nabla^2 \vec{\boldsymbol{u}} - \nabla p + \rho \vec{\boldsymbol{g}} + \vec{\boldsymbol{S}}, \tag{3}$$

(c) energy equation,

$$\frac{\partial}{\partial t}(\rho H) + \nabla \cdot (\rho \vec{\boldsymbol{u}} H) = \nabla \cdot (k \nabla T), \tag{4}$$

where ρ is the density of RT42, $\vec{\boldsymbol{u}}$ is the velocity vector, μ is the dynamic viscosity, p is the pressure, g is the gravity acceleration, k is the thermal conductivity and H is the enthalpy.

The source term $\vec{\boldsymbol{S}}$ in momentum equation due to the reduced porosity in the mushy zone takes the following form,

$$\vec{\boldsymbol{S}} = C\frac{(1-\gamma)^2}{\gamma^3 + \varepsilon}\vec{\boldsymbol{u}}, \tag{5}$$

where C is the constant reflection of the mushy zone morphology. This constant varies between 10^4 to 10^7 and sets at 10^5 at this paper. ε is a small number (0.001) to prevent division by zero. γ is the liquid fraction that is generated during the phase change between the solid and liquid state when the temperature is $T_l > T > T_s$, which can be defined as,

$$\gamma = \begin{cases} 0 & if\, T < T_s, \\ 1 & if\, T > T_l, \\ \frac{T-T_s}{T_l-T_s} & if\, T_l > T > T_s. \end{cases}$$

The enthalpy H in the energy equation is computed as the sum of the sensible and latent enthalpy: $H = h + \Delta H$. The sensible enthalpy h can be expressed as,

$$h = h_{ref} + \int_{T_{ref}}^{T} c_p \Delta T, \tag{6}$$

where h_{ref} is the reference enthalpy at the reference temperature T_{ref}, and c_p is the specific heat. The latent enthalpy ΔH can be written in terms of the latent heat of the material L_h,

$$\Delta h = \gamma L_h, \tag{7}$$

which changes between zero (for a solid) and L_h (for a liquid), as $0 < \gamma < 1$.

To solve the governing equations, commercial software Ansys Fluent 17.1 is employed as a solver. The SIMPLEC algorithm is selected for pressure-velocity coupling. The second-order upwind scheme is adopted for momentum and energy equations discretization, whereas the PRESTO scheme is used for pressure correction equations. At the initial time, the solid PCM, copper heater and stainless steel container are all at 26.5°. The constant heat flux q at left side of heater is about $2500 \mathrm{W/m^2}$. The walls of

Table 1. Thermophysical properties of materials used.

Property	RT42	Copper	Stainless steel
ρ_s [kg/m^3]	880	8978	8030
ρ_l [kg/m^3]	760	-	-
c_p [J/kg·K]	2000	381	502
L_h [kJ/kg]	165	-	-
k [W/m·K]	0.2	387.6	16.27
μ [kg/m·s]	0.0235	-	-
T_l [°C]	42	-	-
T_s [°C]	38	-	-
β [K^{-1}]	0.0001	-	-

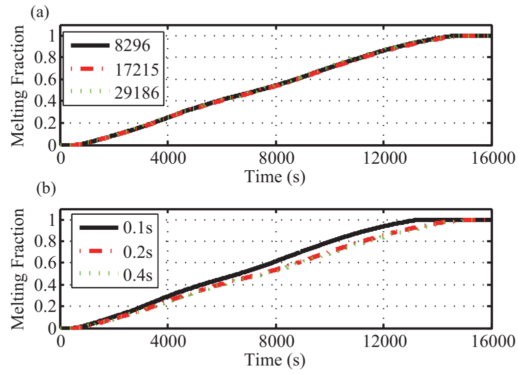

Figure 4. Mesh size (a) and time step (b) independence study for the numerical simulations.

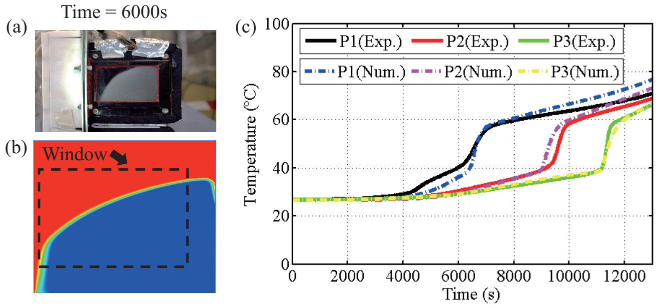

Figure 5. Melting fraction captured from experiments (a) and simulations (b) at 6000s; (c) Temperature at point P1, P2 and P3 varies with time from the experimental measurements and numerical simulations.

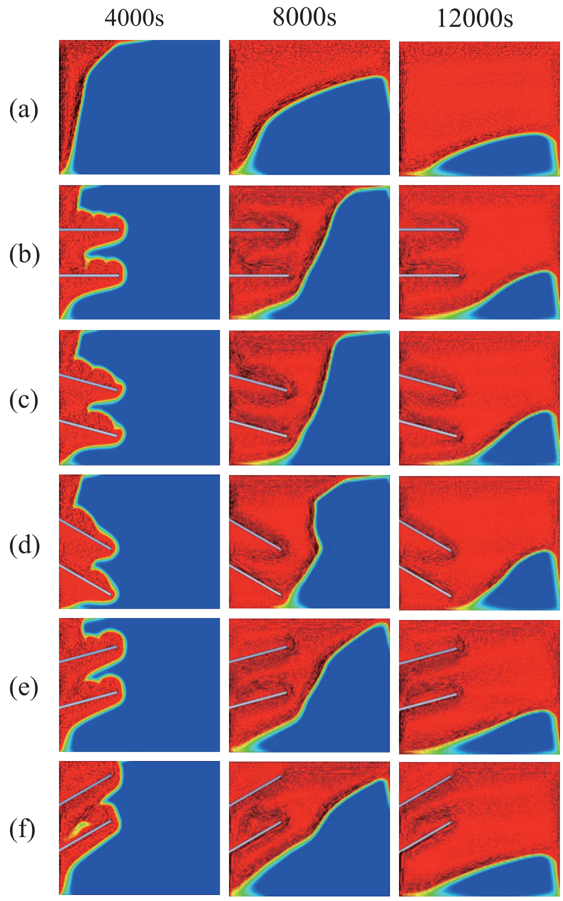

Figure 6. Contours of melting fraction selected at time 4000s, 8000s and 12000s from the cases: (a) No Fin, (b) 0° Fins, (c) $-15°$ Fins, (d) $-30°$ Fins, (e) $+15°$ Fins and (f) $+30°$ Fins.

container are set with adiabatic boundary conditions. A gird and time step independency study is carried out to determine the effects of varying grid and time step size on the numerical solution of the computational model. After the comparisons of melting rate of PCMs as shown in Fig. 4, mesh with 17215 elements and time step at 0.2s are chosen in this study.

RESULTS AND DISCUSSIONS

Validation of Numerical Models

In order to validate the developed melting computational model, initial runs are performed and compared with experimental data obtained from the PCM 'No Fin' test. The melting fraction selected at time 6000s is shown in Figs. 5 (a) and (b). It can be seen that inside the viewing window zone, the present simulation and experiment capture show good consistent on the melting fraction. Temperature evolution with time at points P1 (97, 68.8), P2 (97, 42.2) and P3 (97, 21.5) are also compared. Good agreement is observed again.

Effect of Parallel Fins with Oblique Angles

Numerical simulations are carried out for various cases to study the effects of different oblique angles for parallel fins using in PCM-based heat recovery system. Figs. 6 (a) to (f) present the contours of melting fraction with natural convection driven flow represented by arrows for the cases: No Fin, 0°, $-15°$, $-30°$, $+15°$ and $+30°$ Fins when the flow time is 4000s, 8000s and 12000s, respectively. With the heat generated from copper plate at left, PCMs melt firstly from the top left corner, then to the center part and complete at the bottom right corner due to the natural convection. When the parallel fins added, the PCMs around the fins also melt firstly under the heat transfer. With the comparison between the parallel fins in different oblique angles, it can be found that 0° and $\pm15°$ Fins has stronger natural convection driven flow than the $\pm30°$ ones when the flow time at 8000s and 12000s.

A quantitative comparison by average melting fraction of PCM domain varying with time is also performed following the definition,

$$\mathrm{MF} = \int\int \frac{S_{[T>T_l]}}{S_{[\text{total}]}} dxdy \tag{8}$$

where $S_{[T>T_l]}$ is the area that the PCMs have completely melts to liquid if its temperature is higher than T_l = 42°C, and $S_{[\text{total}]}$ is the total area of PCMs at initial solid state. The detailed results for all simulated cases are plotted in Fig. 7. Compared with 'No Fin' case, PCMs melting rate is enhanced when the fins are added no matter what the oblique angle is, especially at the initial stage ($t < 8000$s). After the flow time t over 8000s, the enhance effect is not so obvious. Another finding is fins with oblique angle in $-15°$ shows a little faster on the melting rate than the other parallel fins.

To further qualify the oblique angles effect on PCM melting for parallel fins, the enhancement ratio evolution with time is also calculated according to the equation,

$$\mathrm{ER} = \frac{\mathrm{MF}_\theta - \mathrm{MF}_{\text{no fin}}}{1} \times 100\% \tag{9}$$

where MF_θ means the melting fraction of parallel fins with a oblique angle θ, and $\mathrm{MF}_{\text{no fin}}$ is melting fraction of 'No Fin'

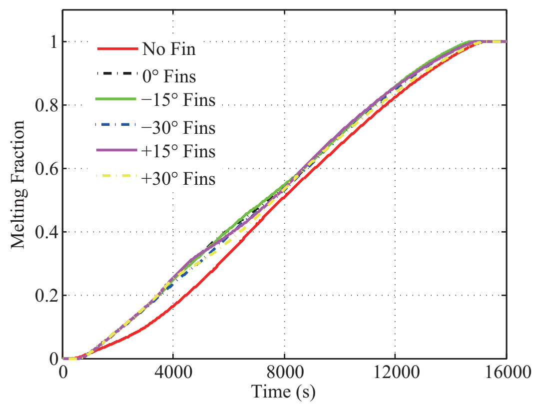

Figure 7. Comparison of melting fraction between the cases: No Fin, 0°, $-15°$, $-30°$, $+15°$ and $+30°$ Fins.

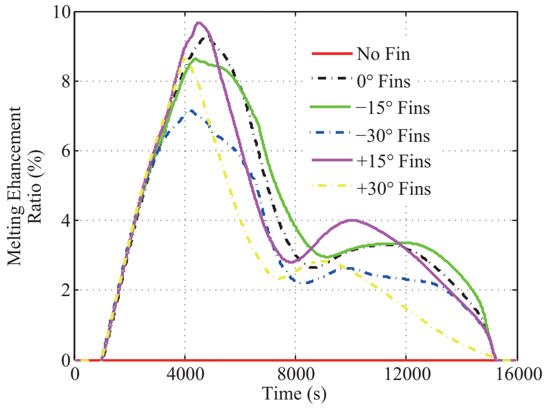

Figure 8. Calculation of melting enhancement ratio for the cases: No Fin, 0°, $-15°$, $-30°$, $+15°$ and $+30°$ Fins.

taken as the base line. It can be seen that the enhancement ratio of parallel fins in different oblique angles firstly increases to its maximum value when t is around 4000 $\sim$ 5000s, after the peak point, it drops quickly and then slowly. Parallel fins in $-15°$ angle with a maximum value about 10% shows the best performance, followed by 0° and $+15°$ fins, and then $-30°$ and $+30°$ fins. It indicates that a small oblique angle for the fins such as $-15°$ can enhance the heat transfer when PCMs melt, but it is not helpful when the angle becomes larger.

CONCLUSION

To enhance the PCM melting for thermal energy storage, the parallel fins with five different oblique angles were proposed. The two-dimensional transient numerical model was built on the basis of Navier Stokes equations in the presence of natural convection. The numerical model was well validated by the experimental results. The PCM-based heat recovery process involving parallel fins with oblique angles of 0°, $\pm15°$ and $\pm30°$ was simulated together with 'No Fin' one. The results showed that the fins with a small angle $-15°$ could improve the heat transfer for PCMs melting about 10% on the basis of the 'No Fin' case, which was the best comparing with the others in the present study. If the oblique angle increased to a larger one, the effectiveness was reduced.

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